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ABSTRACT

This booklet is designed to make available research findins concerning distance running with interpretations, for practical applications, and to point out areas of needed research. Chapter 1, "Describing the Distance Runner," considers the following aspects in relation to the distance runner: a) anatomical characteristics, b) aging, c) strength and reaction time, d) cardiac hypertrophy and electrocardiogram irregularities, e) vital and maximal breathing capacity, f) maximal oxygen uptake, and g) psychological characteristics. In chapter 2, "Training the Distance Runner," the terms "interval training," "Holmer fartlek," "overdistance running," and "Lydiard type" are defined. Also interval and overdistance training, training pace and frequency, and nutritional considerations are discussed. In chapter 3, "In the Long Run," some physiological responses during the distance race and pacing are considered, and the advantages and disadvantages of warming up are discussed. Chapter 4, "Environmental Influence on Distance Running," discusses the effects of running in the heat, in the cold, and at high altitudes. A bibliography is included at the end of each chapter. (PD)

WHAT RESEARCH TELLS THE COACH ABOUT

DISTANCE RUNNING

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Prepared by
David L. Costill
Ball State University

In cooperation with the

National Council of State High School Coaches Associations

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FOREWORD

This is the third publication in the series of booklets titled "What Research Tells the Coach" about a particular sport or activity. It was prepared under the direct supervision of the Research Council of the American Association for Health, Physical Education, and Recreation. The purpose of these booklets is to make available to coaches pertinent research findings with interpretations for practical applications. Also, areas of needed research are pointed out, and a list of research references concerned with the particular area or specific sport is included.

The author of this booklet, David L. Costill, is an outstanding research investigator whose area of interest is distance running. He is currently the director of the Human Performance Laboratory at Ball State University, Muncie, Indiana. He has done and is doing a number of studies in connection with the subjects involved in the famous Boston Marathon. We believe this contribution is one of the most outstanding of its kind yet published. One of the reviewers made the following comments: "The manuscript is by far the best that I have read covering training for distance running. Congratulations upon getting this quality of performance."

There has been no attempt made here to do more than let the coaches know what has been found out about distance running. This is followed by an interpretation of these findings. It is hoped that the modern coach is familiar with research techniques and terminology; however, a minimal use of technical language is made. It is also hoped that this publication may open new doors and suggest new ideas to the modern track coach.

JOHN M. COOPER

PREFACE

Sporting trends have taken many directions in recent years, but few athletic contests offer a greater challenge than the test of matching one man against another, equipped only with the desire and a cultivated capacity to tolerate the prolonged, exhaustive task of distance running. It is not too surprising to realize that man has always been driven by an inner desire to learn more about his own physical and psychological limits. Those who have attempted distance running learn very quickly the price that must be paid in order to push oneself forward while an inner voice seemingly demands a cessation of all physical effort.

This booklet has been prepared for the benefit of all coaches and runners who wish to evaluate their current distance running programs in the light of known facts based on scientific research. Distance running as defined here is all races of two miles or more; however, research concerned with the one-mile run has been included when the findings are believed to have implications for the longer distances. Attempts have been made to incorporate research from many related scientific areas. Some aspects of distance running have been extensively researched. A volume of information, for example, has been published relative to the effects of altitude on physical performance. For that reason, only a summary of these research materials has been included in this monograph.

In selected areas related to distance running, very little research was available. In these cases recommendations have been made for future investigations. The author has attempted to research some aspects of distance running where a sizable void was found. It is hoped that the contents of this booklet will provide a working base for coaching distance runners to achieve greater performance levels.

DAVID L. COSTILL

1. DESCRIBING THE DISTANCE RUNNER

Traditionally, scientists and distance-running coaches have shown keen interest in the unique qualities which enable the distance runner to perform exhaustive physical exercise for extended periods of time. While the investigator has been stimulated to examine these endurance qualities for a deeper understanding of man's ultimate performance capacity and stress tolerance, the distance-running coach has been concerned with individual potential and the prediction of competitive success.

The following discussion is a summary of past and current research describing the anatomical, physiological, and psychological characteristics of successful distance runners. While most of the investigations reported here attempt to show innate qualities typical of "top-flight" runners, the acute and chronic influence of endurance training must be given prime consideration when this information is applied to potential success in competitive distance running.

Anatomical Characteristics

As early as 1899, the unique physical dimensions of distance runners were reported by Williams and Arnold in the *Philadelphia Medical Journal* (Vol. 3, p. 1233), following the Ashland-Boston Marathon race. The competitors were generally described as small and thin. Since that time, numerous studies have reported more specifically the heights, weights, and body compositions of various groups of distance runners (11, 15, 16, 30).

While no single weight level is identified among outstanding distance runners, Hirata (21) suggests that "as the distance increases the runners become smaller." Using the athletes of the 1948 U.S. Olympic team as subjects, Cureton noted that distance runners were of various heights, markedly meso-ectomorphic with thin antero-posterior abdominal depth, and had narrow shoulders. The average height and weight of all the Boston Marathon champions from 1897 to 1965 was 67.1 inches (range: 61-74 inches) and 135.4 pounds (range: 108-173 pounds) (28).

When superior and inferior groups of distance runners were compared, no difference was found between the average height of the groups (11). However, the superior runners were found to be significantly lighter. The primary reason for this weight difference appeared to be a low percentage of body fat among the better runners. These findings agree with Crakes' research on 11 milers at the University of Oregon in 1960 (13).

Since fat and massive bone structures serve as dead weight, it is easy to understand the advantage attributed the endurance runner who exhibits small bones and minimal amounts of fat. The normally accepted percentage of body fat for young men, ages 18-25 years, is 8-12 percent. Studies have reported groups of cross-country and marathon runners with values as low as 2.4 percent (7).

Kireilis and Cureton (23) found significant negative correlations of the magnitude of −.578 to −.264 between performance of strenuous physical exercise and external fat on the body. In strenuous endurance running, the fat on the abdomen and buttocks seemed to be more of a handicap, with negative correlations in performances, −.737 to −.588, than fat on the thighs and cheeks, −.394 to −.226.

Endurance runners are characterized as having proportionately longer legs and shorter trunks per total height than the normal male (5). However, they have below average thigh and lower leg girth, narrow hips and shoulders, and a shallow chest. Behnke (4) reported that distance runners were deficient in arm girth compared with their chest size and leg development.

Aging

Persons even vaguely familiar with distance-running competition are aware of the ability of distance runners to improve with age and to attain their greatest success in their late 20's or early 30's. It is not unusual to observe men competing in long distance runs at the age of 50 years. A classic example was Clarence DeMar, "Mr. DeMar-athon," who won his seventh Boston Marathon at the age of 42 years, placed seventh at the age of 50 years, and finished 78th in a field of 133 runners at the age of 65 (28).

A tabulation of the ages of all the distance runners in the 1964 Olympic Games revealed an apparent trend (21). The average ages for the competitors in the 5,000-meter, 10,000-meter, and marathon races were 27.0, 27.7, and 28.3, respectively. The average age of all the Boston Marathon champions from 1897 to 1965 was 27.1 years, with a range from 18 to 42 years (28).

Strength and Reaction Time

On most tests of strength and reaction time, distance runners tend to be below average (11, 35). A randomly selected group of male college students had a dominant hand grip strength of 117.3 pounds, while 38 cross-country runners scored 106.1 pounds. The same random male group averaged 20.9 inches on a vertical jump test, but the cross country runners averaged only 18.6 inches. It is interesting to note that Robert Fitts, 1966-67 NCAA College Division 3-mile, 6-mile, and cross-country champion, could vertical jump only 13.5 inches (11). Cureton (15) concedes that endurance runners are not usually strong (gross strength), but are normal when strength is determined in relation to their body weight.

Westerlund and Tuttle, in 1931, found a significant relationship (.863) between running speed and hand-eye reaction time. The mean reaction time of the distance runners (.169 sec) was significantly slower than that of the sprinters (.131 sec) and middle distance athletes (.149 sec).

The key physiological component essential for success in distance running is a superior, well trained cardiorespiratory system. For this reason, the major research emphasis on distance runners has been centered around the cardiac output, heart size, electrocardiogram, and metabolic limitations of these athletes.

Although most researchers are aware of the variety of factors (emotional, environmental, previous activity, etc.) that can influence the resting heart rate, distance runners have been known to possess exceptionally low basal and resting heart rates. While studying for his Ph.D. degree in 1938, Glenn Cunningham (14) reported that the best combination of measures to differentiate extreme ability in the long distance events is resting pulse rates and pulse rates after exercise. A number of internationally ranked distance runners have reported heart rates below 40 beats per minute.

Under very controlled conditions, resting and basal heart rates have been found to correlate quite highly (−.61 and −.65, respectively) with cross-country running speed (11). However, one must remember that both basal and resting heart rates are significantly influenced by training, which seems to be the primary cause for bradicardia among athletes trained for endurance competition.

Cardiac Hypertrophy and ECG Irregularities

Smith *et al.* (33), in 1962, studied the electrocardiograms of marathon runners competing in the British Commonwealth Games. They noted high voltage of the QRS complex and somewhat enlarged T-waves. Similar findings were reported by Arstila and Koivikko (1) in 1966. Electrocardiographic and vectorcardiographic studies of 46 endurance athletes showed that a large proportion had cardiac hypertrophy. Similar findings of ventricular hypertrophy have been verified by X-ray shadow estimates of heart size (15). Paavo Nurmi, seven times Olympic champion, was found to have a heart nearly three times normal size (5).

An interesting difference observed between older and younger athletes is that the former exhibited more electrocardiographic signs of left ventricular hypertrophy than of right ventricular hypertrophy, while the latter showed left ventricular hypertrophy less frequently than right ventricular hypertrophy. The predominance of the right ventricle may be evidence of a comparatively greater right-side work hypertrophy during the first years of training, after which the left ventricle gains comparatively greater weight and becomes dominant.

In addition to signs of hypertrophy, intraventricular conduction defects of minor degree have frequently been observed among trained runners by several investigators (17, 18, 34). While such findings might cause considerable alarm when observed in untrained, middle-aged men, these abnormalities have little medical significance when occurring in young, symptom-free athletes.

Post-mortem examination of the distance runner's heart is seldom possible; however, findings in the case of Clarence DeMar, who competed in over 1000 long-distances races during his life, revealed a significantly enlarged heart. In 1958, DeMar was diagnosed as having peritoneal carcinomatosis, but he continued to train to within two weeks of his death. His heart weighed 340 grams (average male heart 300 grams). The left ventricular wall was 18 mm thick (average 10-12 mm), and the right mm (average 3-4 mm). The valves were normal, but the coronary arteries were estimated to be two or three times normal size. The large coronary vessels, other things being equal, insured an adequate oxygen supply to cardiac muscle when the demands were great, and this probably reduced to a minimum the need for hypertrophy of the heart. The evidence in DeMar's case, after 49 years of strenuous physical training, was one of notable compensatory changes.

Other Circulatory Considerations

While distance runners possess a markedly low resting heart rate, the volume of blood ejected from the heart with each beat (stroke volume) has been reported to be nearly double the normal value (19). The large stroke volume is a product of ventricular enlargement and more complete emptying with each ventricular contraction. Consequently, the endurance athlete's heart accomplished its work at rest and during exercise with considerably greater efficiency than the average person's heart.

Several studies have shown that indirect blood pressures recorded at rest are not significantly related to endurance capacity (11, 15). Since training has been found to lower an athlete's diastolic blood pressure, it is not surprising to find studies which report normal systolic pressures (120-122 mmHg) and low diastolic values (50-63 mmHg) among college cross-country runners (11). Brachial pulse waves, as measured by a heartometer, have no more value in predicting cross-country running time than can be assumed from the resting pulse rate (27).

The blood composition of distance runners does not differ significantly from that of other endurance athletes. The ratio of red blood cell volume to plasma volume (hematocrit) and hemoglobin concentrations have been found to increase with training, but do not relate to distance running success.

Attempts have been made to utilize various physical fitness tests to identify potential endurance running ability. While trained cross-country runners score significantly higher than other trained athletes on the Harvard Step Test and Bruce Physical Fitness Index, these tests are not useful predictors of competitive running time (11, 29). When the runners exercised to exhaustion on the treadmill, their duration of exercise was reported to correlate quite highly with competitive running success (15).

Vital Capacity and Maximal Breathing Capacity

The maximal volume of gas that can be expelled from the lungs by forced effort following a maximal inspiration (vital capacity) can be significantly enlarged as a result of years of training (6). It is not surprising, therefore, to find that distance runners are notedly above average in vital capacity. One study observed mean vital capacities (BTPS) of 5.79 liters and 5.63 liters for nine and eight cross-country runners, respectively (1). The mean vital capacity for average, untrained men of the same age is 4.8 liters (9). When computed on the basis of body size (height, weight, or body surface area), distance runners score even higher as a result of their small vertical and lateral dimensions.

Training for distance running develops tremendous respiratory muscle stamina and strength. Maximum breathing capacity (MBC) is the maximum volume of air that can be breathed per minute (10). While the normal male is said to have an MBC of from 125 to 170 liters per minute, a group of 10 college cross-country runners had a mean MBC of 207.5 liters per minute (7). One might theorize that well trained distance runners possess a superior respiratory musculature and/or reduced respiratory resistance which might enable them to carry on external respiration during exercise at a level that is easily within their capacity. During exhaustive running, highly trained distance runners have been able to breathe over 120 liters per minute for more than twenty minutes (12). Among untrained and most trained men, such a large minute volume is normally attained only during the final minutes of exercise and can be maintained for only a few minutes.

Maximal Oxygen Uptake

The physiological capacity of the body to consume oxygen during exhaustive exercise is dependent upon pulmonary ventilation, pulmonary diffusion, oxygen-carrying capacity of the blood, cardiac output, and arteriovenous difference in oxygen saturation. Based on the preceding discussion, it has become quite evident that a highly trained distance runner possesses both superior circulatory and respiratory systems. It is not surprising, therefore, that researchers have observed superior maximal oxygen uptake values among nationally- and world-ranked runners (2, 7, 11, 12, 26, 31, 32).

In 1952, Astrand (3) reported a correlation of .98 between maximal oxygen uptake in liters/minute and body weight, using 115 males between the ages of 4 and 33 years. Buskirk and Taylor (8) examined the relationship between maximal oxygen intake and several measures of body size and composition and found that body weight correlated .63 with maximal oxygen intake in liters/min. When calculated in ml/kg of body weight/min, the maximal oxygen uptake of distance runners is exceptionally superior to most other athletes. Table 1 presents the maximal oxygen uptake values for several groups of highly trained distance runners.

TABLE 1. MAXIMAL OXYGEN UPTAKE VALUES OF NATIONAL AND WORLD CLASS DISTANCE RUNNERS

Researcher	N	Subjects	Max. V_{O_2} (l/min)	Max. V_{O_2} (ml/kg/min)
Saltin (32)	5	World Class Distance Runners	5.03	77.5
Robinson (31)	1	Don Lash	5.35	81.4
Costill (12)	4	Nationally-Ranked Distance Runners	4.75	75.5
Lindsay (26)	1	Peter Snell	5.50	72.3
Kollios (24)	5	Collegiate Cross-Country Runners	4.92	72.6

While comparing distance runners of varying ability, the author obtained a correlation of .82 between maximal oxygen uptake (ml/kg/min) and distance-running performance (4). Figure 1 illustrates the distribution of maximal oxygen uptake (ml/kg/min) values for 17 cross-country runners in relation to their running times for 4.7 miles.

Based on physiological research with distance runners, one must conclude that the best single predictor of running success is the maximal oxygen uptake value (ml/kg/min).

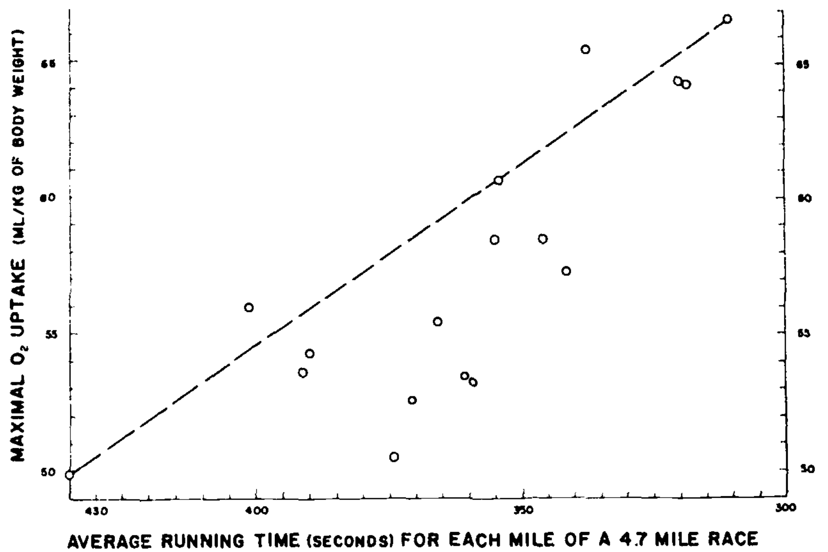

FIGURE 1. The relationship between maximal oxygen uptake (ml/kg/min) and distance-running performance.

Psychological Characteristics

Very little research has been attempted to evaluate the personality or intellectual or emotional characteristics of distance runners. The only psychologically-oriented study along these lines was conducted by Husman (22), who researched the aggressive natures of various groups of college athletes and nonathletes: boxers (N=9), wrestlers (N=8), cross-country runners (N=9), and a control group (N=17). The Rosenzweig Picture-Frustration Study, Murray's Thematic Apperception Test, and a 20-sentence completion test were used to measure aggression. It was concluded that the cross-country runners tended to aggress outwardly (extrapunitively) more than the boxers. The runners were also found to be extrapunitive and less impunitive than the control group members, thus aggressing against persons and objects in the environment more than the control group.

Lakie (25), on the other hand, reported no difference among the personalities of basketball, football, tennis, golf, wrestling, and track participants. It is quite evident that more extensive research should be undertaken to better describe the psychological make-up of the distance runner.

Summary

The distance runner is generally characterized as an ecto-mesomorph, low in body fat, with thin antero-posterior abdominal depth. Success in distance running seems to improve with age, the greatest performance being achieved during the late 20's or early 30's. Strength does not seem to be a prime requirement for successful distance running. However, definite circulatory, respiratory, and metabolic advantages are observable among world class runners. The best single predictor of distance-running success is the maximal oxygen uptake (ml/kg/min). There is a need for research to identify the psychological components of the distance runner.

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2. TRAINING THE DISTANCE RUNNER

The most ideal training program for preparing a distance runner for competition is equivocal. There exist nearly as many different types of training programs as there are runners. Most of these programs are based upon tradition, copied from the ideas of successful runners and/or founded upon a combination of theories and philosophies. It is rather unlikely that any one type of training will produce the most perfect results for all runners, since the combination of anatomical, physiological, and psychological factors which compose the distance runner are too divergent. Nevertheless, it is not unrealistic to expect to identify training procedures which will generally produce desired outcomes.

Among distance runners, training is commonly categorized as either speed or overdistance work. Speed work may take the form of interval training or Holmer fartlek type running. Overdistance work refers to the Lydiard type run. Since a great deal of variation exists among the interpretation of training terminology, the following definitions will be utilized in later discussion:

1. *Interval training* is a system of repeated efforts in which a measured distance is run at race pace or faster alternately with measured recovery periods of low activity.
2. *Holmer fartlek* is defined as "speed play," free-type running done over an indefinite distance for an indefinite time with some segments of the run performed at a faster pace than others, depending on the disposition of the athlete.

3. *Overdistance running* involves training at distances greater than those of actual competition and may include continuous runs of six to ten miles or more. The pace of such runs is normally predetermined and is usually only slightly slower than the runner's racing pace.
4. *Lydiard type* running employs very long continuous running of 10 to 30 miles or more at a slow, steady pace and is performed well within the capacity of the runner.

Interval Training

The efficiency of various interval training programs is not clearly understood and the amount of research is limited. Regardless of the distance run in the competitive event (one mile to 10,000 meters), some track coaches favor short distance interval training programs while others choose long distance. Both programs have produced Olympic champions. Most evidence at the present time tends to support a work session with repeated short, fast bouts of exercise not exceeding 60 to 90 seconds in duration. This is true whether the competitive event be a long or short distance.

Christenson (10), using two well conditioned subjects, compared the effects of intermittent running on a treadmill at a speed of 12.4 miles per hour with continuous running at the same speed. The work and rest intervals for the intermittent condition were 30 seconds each. He reported the length of the work period to be most critical, whereas the length of the rest pauses as well as the total work output were of secondary importance. During the experiment, in which the two subjects ran continuously at 12.4 miles per hour, they became exhausted after approximately four minutes. Each experienced maximal oxygen consumption values, high blood lactates, and high pulse rates. On the other hand, when the subjects ran intermittently, they experienced only slight increases in blood lactates, lowered oxygen consumption values, and a constant heart rate (140-150 beats per minute), even though the total exercise period was nearly twenty minutes. He concluded that the intermittent condition was (1) a more economical way of work, (2) more demanding on the circulatory and respiratory systems, and (3) more favorable to the development of efficient chemical reactions.

In another experiment, Christenson (10) found that alternating work-rest periods of as short as 5 to 15 seconds would produce results similar to those above. He again pointed out that little if any increase in blood lactate occurred under these conditions. Apparently such short exercise periods with intervening rest periods do not produce significant amounts of lactate. This is advantageous since lactate-producing exercises impede performance by (1) reducing the contractile power of the musculature and consequently the speed of running, and (2) leading to a more rapid fatigue (34).

A minimum of 90 seconds (approximately a 600-yard run) has been found necessary to overload the circulatory and respiratory systems to increase aerobic work capacity significantly (35). It was also reported that endurance performance and oxygen requirement for an "all-out" treadmill run tend to improve and increase as the total number of repetitions is increased; that is, as the individual repeatedly runs for periods lasting at least 90 seconds, he increases both the capacity for oxygen uptake and the endurance required for sustained work.

Noon (35) reported the effects of two interval training programs during a 12-week period. He studied electrocardiographic recordings, blood test samples (hemoglobin, hematocrit, and corpuscular hemoglobin concentration), and time on the 5000-meter run. The training programs consisted of (1) a short-distance group which trained at distances ranging from 30 to 440 yards at a fast pace, and (2) a long-distance group which trained at distances ranging from 880 yards to two miles, and on long steady runs from 3 to 15 miles (six to eight minutes per mile). Both groups covered 23 to 45 miles per week. The findings indicated that speed training caused more rapid positive changes in electrocardiographic and blood test results and in running time for 5000 meters. The overdistance training caused the same changes but with fewer extreme results and at a slower rate. Noon concluded that both types of training should be employed in planning long-range work schedules since there were positive physiological changes unique to both long- and short-distance training methods.

The work interval consists of two parts—the work distance and the work rate. Both are subject to change, either singly or jointly, at the discretion of the coach or runner. Most modern distance-running coaches advocate speed work as a portion of training, although there are differences in their beliefs as to when and to what extent speed is of prime importance. With regard to endurance, however, most authorities agree that mileage is the first consideration and that the runner should gradually increase the duration of his daily mileage.

Egolinski (19) came to the following conclusions with regard to load size, rate of work, and duration of work, respectively: Muscular endurance increased when the resistance was 15-30 percent of the maximum strength of the muscle; training at the low and middle rates was 3-6 times more effective for the development of endurance; and the increase in endurance was slightly greater with the work of long duration than with the work of shorter duration. He seemed to favor work periods of long duration at a low rate of work for the development of endurance.

In addition, Astrand and others (5) studied thirty girl swimmers who had won nine Swedish national championships. Astrand reported that the better endurance performers trained more times per week and swam a much greater total distance per week.

Another approach to determining the proper distance is the use of exercise heart rates. For example, Balke (6) proposes that a heart rate of 180 beats per minute be used to measure cardiorespiratory capacity because this rate represents a "physiological point at which circulatory-respiratory limitations become manifest;" that is, when the heart rate reaches 180 beats per minute, it no longer benefits the individual to continue the exercise, as the heart can neither fill nor empty completely. These findings are in agreement with those of Gerscher and Raindell as reported by Doherty (16).

At the other end of the continuum, however, there appears to be some question. Karvonen (26) exercised men on a treadmill for 30 minutes a work period, four to five times per week. He found that a pulse rate of 153 beats per minute was necessary to improve performance. Studies involving three groups of men walking 10, 20, or 30 kilometers daily showed that all three groups improved fitness in only ten days, despite the fact that pulse rates never exceeded 120 beats per minute.

However, evidence to the contrary was presented by other authors. Yakovlov *et al.* (43) conducted an experiment involving three groups of men who trained for five months doing the same amount of work and using the same exercises. Each group ran 30 meters at maximum speed. The only variable factor among Group I, Group II, and Group III was the resting interval—one, two, and three minutes respectively. The results showed there was improvement in all three groups, but it was greatest in Group I and least in Group III. Therefore, the greater and more varied training effects were obtained when the recovery interval between the runs was short.

Aerobic vs. Anaerobic Exercise

Much of the controversy over whether it is best to run long distances at a slow pace, or short distances at a fast pace, centers around the concept of aerobic (submaximal) and anaerobic (maximal) exercise and the concomitant physiological adaptations of the body.

Basically, aerobic exercise means that the individual can sustain prolonged exercise because his oxygen consumption during exercise is sufficient to meet the demand of the active muscles. However, if one is not able to meet the oxygen demand of exercise via his oxygen uptake, he must draw upon the anaerobic reserves of the working muscles. As a result, lactic acid and other metabolites, which will eventually cause the cessation of exercise, are formed. In comparing runners performing similar amounts of work, the one who is able to delay the utilization of his energy reserves will be able to work longer. Long-distance training is thought to place greatest stress on the aerobic mechanism. However, some researchers have presented evidence to indicate that the reserves for anaerobic work may play a principal role in prolonged aerobic running (7 23, 40).

Anaerobic running has been shown to bring into play the stored energy reserves of the body. This occurs mainly as a result of the breakdown of glycogen into lactic acid. However, it has been shown that the rate of lactic acid accumulation is much slower when short periods of exercise are followed by short rest periods (9, 10). Thus, more work can be performed in this manner. Therefore, running short distances at a fast pace, where breathing is not necessary, will develop the anaerobic mechanism.

Karpovich (25), Heusner (22), Robinson (37), and others apply this thinking in the following manner. They suggest that an increased oxygen supply in the longer races is most imperative. Therefore, if the pace is moderate enough, the oxygen intake can meet all body needs, but if the pace is such that the oxygen inspired is not assimilated in adequate portions to meet the energy cost, then the unoxidized substances will begin to accumulate, mainly in the form of lactic acid.

However, within the framework of the interval training concept, the performance of several short sprints is thought not only to develop the anaerobic mechanism (i.e., increased tolerance for oxygen debt), but to stress the aerobic mechanism at the same time. Yakovlov (43) reported that training by short, fast exercises of maximal and submaximal intensity led to a varied adaptation by increasing the potential range of both anaerobic and aerobic provision of energy for work.

Heusner suggests that after a few short sprints where the energy cost is supplied anaerobically, metabolic processes must turn to the aerobic mechanism to supply the energy for further work. Therefore, as Dill (15) reports, training at short distance at rates of speed faster than competitive pace results in an

> increased capacity for supplying oxygen and at the same time commits higher levels of energy exchange before the lactic acid debt begins to accumulate. In maximal work, the athlete is able to supply more oxygen and also contract a greater oxygen debt as a result of his training program.

It is now logical to assume that the ability to accumulate an oxygen debt is more important to performances at a short distance, whereas continuous oxygen uptake is more important to performance of work consisting of a slower pace running over longer duration of time, as in a distance event.

Ohio State University Research on Interval Training

While the preceding discussion reveals many interesting facts about interval training, some basic questions still remain unanswered. How often are interval workouts required each week? What distance should be run? Members of the departments of preventive medicine and physical education at the Ohio State University conducted a series of investigations between 1965 and 1967 to answer these questions (8, 20, 30).

This research has significant meaning for the distance runner because the criterion measures of fitness improvement were the maximum oxygen uptake and other tests of circulorespiratory performance.

In an attempt to determine the frequency of interval training required to produce an improvement in cardiorespiratory endurance, the researcher compared a training frequency of four days per week to a program of two workouts per week (20). The two groups, of approximately 25 subjects each, were young, healthy male students who worked for seven weeks in an interval training program. The four day/week program consisted of two days of short distance running (55 to 220 yards) with as many as 16 to 20 repetitions, and one day of both short- and long-distance running. The two day/week program consisted of one day of short-distance running and one day of both long- and short-distance running. All running was performed at a fixed pace with a given work-to-rest ratio. Based on this procedure, it was found that the cardiorespiratory fitness of young men can be improved by a seven-week interval training program with as few as two workouts per week. It was further shown that such improvement is similar to that obtained from the same program with four workouts per week. The biggest and, in fact, the only difference between the two groups was found in recovery heart rate, the four day/week group showing greater improvement. It was believed that if the program were longer than seven weeks in duration, the two day/week group might tend to show less overall improvement than the four day/week group. However, additional research over a 13-week period produced identical results to those obtained during the initial seven-week project (31).

In another series of investigations, an attempt was made to determine which of three interval training programs would produce the greatest improvement in cardiorespiratory endurance as measured by maximal oxygen consumption, Harvard Step Test, the Army Physical Fitness Test, and time trials for the 220- and 880-yard runs. The subjects of the investigation were placed in three matched groups. Each of the three groups worked for eight weeks (37 days) in an interval training program administered five times per week, one hour per day. One group participated in a program consisting entirely of short-distance running (55 to 220 yards) with as many as 16 to 20 repetitions. The second group participated in a program consisting of running relatively long distances (660 to 1320 yards) with no more than 5 to 6 repetitions at a fixed pace with the same work-to-rest ratio as the short-distance group. The third group trained by mixing both short- and long-distance running on an equal and alternating basis.

Based upon their findings, the researchers concluded that short, repetitive running is necessary for maximum improvement of cardiorespiratory endurance; long, less frequently repeated running is less necessary than is short distance running; and both types of running are probably helpful for proper leg conditioning, reduction of leg injuries, and for variety and motivational purposes.

Overdistance Training

While most coaches generally agree that overdistance running is beneficial and an important training foundation for distance runners, they do not totally agree upon the duration, pace, and application for such training. A careful review of the research literature provides little assistance in solving this controversy.

One researcher, Noon (35), noted a definite distance-running (5000 meters) advantage from overdistance training as compared to speed training. He suggested that overdistance work mentally toughened the runners to compete at the 5000-meter distance. Since one of the primary psychological obstacles for the distance runner is the duration or distance of the race, Noon's thinking would seem justified. In races of 10 miles or more, it often becomes a problem to keep moving after an exhaustive hour or more of running. While only a small portion of a runner's discomfort can be described as psychological, one's ability to tolerate such pain is certainly compounded by the length of time one is exposed to such fatigue. Overdistance training, therefore, would assist the runner in adapting to long periods of exhaustive discomfort.

Interval vs. Overdistance Training

Interval training, or speed work, has been given credit for many of the improvements in middle- and long-distance running performances. Yet no conclusive scientific information has been presented which would favor interval-type training over continual (overdistance) running. The few studies which have attempted to shed some light on this controversy appear to offer conflicting results.

McDavid (33) found that when total work was held constant, interval training offered no better results for endurance than uninterrupted running. He theorized that with intermittent work, presumably under anaerobic conditions, the runner does not seem to obtain as great a lactic acid oxygen debt as is common to prolonged aerobic work (continuous running). The rest periods within interval training permit part of the oxygen debt to be repaid. Thus, the subject begins the next bout partially recovered.

Schleusing and Deetz (40), in 1964, compared interval and uninterrupted training among 80 laboratory rats. As opposed to McDavid's work, Schleusing and Deetz observed that interval training caused more marked adaptative reactions of the cardiac and skeletal muscles than the uninterrupted training. Consequently, the physical working capacity of the animals was unequivocally greater after interval training than after uninterrupted training.

Mirwald (34), in 1965, compared two methods of training for the running of the mile. One system involved the use of interval training only, whereas the other was a combination program of interval and fartlek training. It was concluded that either type of training would result in similar improvements in running times for the mile. However, the runners who employed only interval training seemed to incur more injuries.

While the theoretical and philosophical aspects of overdistance and speed training offer diverging ideas, one cannot overlook the success attained by both systems. However, it is somewhat unfair to consider individual feats of success, for cannot every performance be improved upon? How much better might any champion be if his training program were made more nearly perfect?

Since no conclusive results can show a priority for either continuous or interval running, let us consider the so-called "specificity of training." In training it is believed that the runner should practice at rates faster than or equal to his competitive pace. Cureton (12) states:

> The organism must be made so conscious and cognizant of the intended race pace that it eventually becomes a habit (specificity) . . . working at a slower pace will not train the body effectively for the faster pace.

Running at a pace which is slightly faster or equal to the racing pace instills a running rhythm which is more easily accomplished during competition. That is to say, the runner can run efficiently only at a pace which his nervous and muscular systems are accustomed to performing.

Training Pace

The employing of overdistance training for the long-distance runner presents several decisions which must be made prior to each training session. They are the pace (speed) and distance (duration) of the run. Many great marathoners, such as Jim Peters (36), suggest that "it is the pace which kills and not the distance. . . . All training is done at just below racing pace." However, other outstanding running authorities, such as Lydiard (29), advocate very long, continuous running at a slow, steady pace.

While no direct research is available to assist the coach or runner in deciding which distance and pace should be attempted in a given workout session, some information of an indirect nature may shed some light on these two schools of thought. Most of this related research has been undertaken to identify the threshold for cardiovascular endurance development; that is, to determine how much work is required to achieve the physiological changes that are reflected by the highly trained athlete.

Untrained medical students were used as subjects, and treadmill running was instituted for a daily half-hour period for four weeks (30). The speed of the treadmill was adjusted according to the pulse rate of the subjects, so that each man ran at a speed which would maintain a specific, predetermined pulse rate. As exercise tolerance improved and the heart rate slowed for a given workload, the speed of the treadmill was increased to keep the heart rate at the original level. It was concluded that to improve the exercise tolerance of the heart, the intensity of the workout must exceed a critical threshold value. Karvonen expressed this as attaining a heart rate 60 percent of the way between the resting and maximal heart rate. DeVries (14) changed Karvonen's idea into a formula, as in the following illustration: A subject with a resting rate of 70 and a maximum of 200 would have a critical threshold of $70 + .60 \times (200 - 70)$, or 148 beats per minute. Based on extensive laboratory data obtained from distance runners, Table 2 presents the critical threshold for five well trained runners. If the runners expect to gain cardiovascular endurance for their workouts, they must run at a pace that will elicit a heart rate that is equal to, or greater than, the critical threshold heart rate. In the case of the data presented in Table 2, these runners would have to pace their overdistance workouts at an average rate of 7:30 for each mile (8.02 mph). One must remember that such a training pace will produce only a minimal improvement in circulatory endurance. It must be pointed out. however, that subject E.W. utilized overdistance training exclusively at a 7:00-7:30 pace and has produced a 8:55.6 for two miles (indoor).

Astrand (4) has theorized that a runner must train at an oxygen consumption level which exceeds 50 percent of his maximal oxygen consumption value if cardiovascular endurance is to be improved. Table 3 is an attempt to show the relationship between Karvonen's research (26) and the theory offered by Astrand. At the average critical threshold heart rate of 133, these same subjects had an average oxygen consumption of 2.735 liters per minute as compared to their average maximal rate of oxygen consumption of 4.715 liters per minute. These subjects would, therefore, be required to exercise at 57.9 percent of their maximal oxygen consumption capacity when running at their critical threshold heart rate. Although this percentage is slightly higher than that anticipated by Astrand, it would appear to be in keeping with his feelings that the work level must exceed at least 50 percent of the individual's maximum capacity.

TABLE 2. RELATIVE CRITICAL THRESHOLD HEART RATES AND RUNNING SPEEDS REQUIRED TO GAIN CARDIOVASCULAR ENDURANCE
(Data are from the Human Performance Laboratory, Ball State University.)

Subject	Resting H.R.	Max. H.R.	Critical Threshold*	Running Speed (mph)	Running Speed (min:sec/mile)
S.L.	52	188	134	7.58	7:55
S.K.	54	192	132	7.92	7:35
D.K.	50	186	132	8.00	7:30
K.S.	46	192	134	8.10	7:25
E.W.	52	188	134	8.50	7:04
$\bar{X}$	51	189	133	8.02	7:30

* Calculated as described by Karvonen (26).

TABLE 3. OXYGEN REQUIREMENTS BASED ON DATA PRESENTED IN TABLE 2

Subject	Critical Threshold Heart Rate *	V_{O_2} at Critical Threshold H.R. (l/min)	Max. V_{O_2} (actual) (l/min)	% Max. VO_2
S.L.	134	2.271	4.270	53.2
S.K.	132	2.910	4.915	59.2
D.K.	132	3.004	5.126	58.6
K.S.	134	2.800	4.585	61.1
E.W.	134	2.690	4.680	57.5
$\bar{X}$	133	2.735	4.715	57.9

* Calculated as described by Karvonen (26).

We have, therefore, established the lowest level of physical stress that is necessary to develop minimal improvement in circulatory endurance. However, the distance runner is not content with a minimal level of improvement but desires the most optimal work level for the greatest amount of improvement. As has been pointed out earlier, the most important contribution of training to the distance runner is the development of the oxygen transport system. Karlsson and others (24) have studied the training of the oxygen transport system and have concluded that for optimal training of the circulatory system, the load on the oxygen transport system should probably be maximum. This does not mean, however, that the runner must run at an exhaustive pace during each training session. Karlsson pointed out that there is a range of fast running speeds with the same maximum oxygen consumption. The most optimal training pace, therefore, would be the slowest pace at which the maximum oxygen consumption can be attained. This reduction of the speed implies less fatigue (lactic acid accumulation) and also makes it possible to increase the volume of the training.

As an example, Figure 2 illustrates the relationship between treadmill running speed and oxygen consumption obtained from a nationally-ranked distance runner. If we desire to identify the slowest speed at which his body is consuming its maximum amount of oxygen, one need only drop a line (dotted) down to the base line from the initial point of the curve's plateau to select the most optimal running speed.

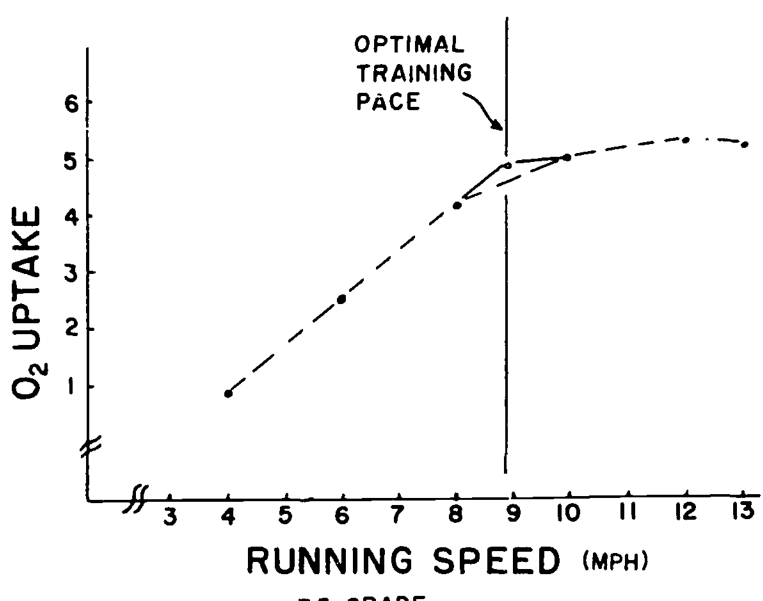

FIGURE 2. Selection of the most optimal training pace as related to oxygen uptake (l/min).

Training Frequency

A great deal of distance running success and improvement within current years has been attributed to the improvement of training procedures. After a careful review of the literature, it is quite evident that the improvement in training techniques is not so revolutionary; that is, the quality of training has not taken so great a change. During the late 1800's and early 1900's, English distance runners were utilizing interval training (not so termed) and working out twice each day (41). The major change appears to be concerned with the quantity rather than the quality of work performed by the runners. Shrubb, who in 1904 ran 50:55 and 9:17.8 for ten and two miles, respectively, and George, who in 1886 ran the mile in 4:12.8, both trained on programs that would seem more like a warm-up by present day standards. During his most strenuous training, Shrubb covered some 35 miles of moderate running in a 7-day period. George, in 1882, reported that he ran fewer than 10 miles per week, most of it at a slow pace. However, both men were reported to have trained twice per day, and they described the use of occasional sprints with desired rest intervals between each.

It appears safe to say that few world-class distance runners train at fewer than 70-80 miles per week. A survey (28) of the 125 entries of the 1962 Western Hemisphere Marathon revealed that 60 percent of the runners trained 45-52 weeks per year. Forty-five percent of the participants trained twice each day, and nearly 40 percent ran more than 100 miles per week. As would be expected, those who finished among the leaders employed all of these training procedures (year-'round, twice per day, and mileage in excess of 100 miles/week).

In 1960, Zeigler (44) studied the rate of cardiorespiratory endurance development produced by all-out exercise one, two, and three times per week. It was reported that twice per week all-out exercise seemed to achieve the greatest percent increase. Increasing the number of exercise sessions per week seemed only to increase the individual variation. There also appeared to be no indication that endurance would not continue to develop, even after 18 weeks of training.

A recent investigation of the benefits of supplementing each daily practice session with an additional early morning continuous run (4.5-5 miles per run) found no greater improvement among the supplemental group than was achieved by the group practicing once each day (38). The criterion measures for comparing one and two practice sessions per day were exercise heart rates during a standard treadmill run (9 mph, 0% grade), recovery heart rates, performance time in the 880-yard run, and running time for the mile. Both matched groups of trackmen (eight runners per group) demonstrated similar rates of improvement among the criterion measures. However, the degree of change varied considerably among the individuals of both groups. One must conclude, therefore, that a supplemental training program may produce greater benefits among selected individuals.

Nutritional Considerations

Several tests on the nutritional aspects of athletics have been published, and numerous researchers have studied the biochemical responses of men during prolonged exhaustive work. The purpose of the following discussion, however, is to review some basic and somewhat revolutionary concepts of postexercise and precompetition nutrition. Fluid ingestion during distance running competition will be discussed in Chapter 3.

It is well known that glycogen is utilized by the muscle during exercise as a primary source of energy, but there is very little information available about the replenishing of muscle glycogen after exhaustive exercise. Goldstein (21) has shown that a humoral factor which decreases the blood glucose concentration is released during exercise. He believed that this humoral factor facilitated the transport of glucose to the interior of the muscle fiber.

Bergstrom and Hultman have conducted several studies to clarify Goldstein's findings and to determine the relationship between muscle glycogen replacement and postexhaustive diets (1, 7, 23). As a result of their research, it has been concluded that the muscle glycogen concentration can be increased considerably by first emptying the glycogen stores through strenuous work and then administering a carbohydrate-rich diet, The resulting benefit of glycogen replenishment is localized to the muscles that have been exercised, without any effect on other muscles. A fat-protein diet following exercise, on the other hand, produces a slow, incomplete replacement of glycogen in the muscle. If carbohydrate is given without previous exercise, only a mild increase in muscle glycogen occurs.

The performance time on a given exercise load can be increased by more than 100 percent by ingesting a carbohydrate-rich diet after exhaustive exercise. Since the working capacity decreases as the muscle glycogen is depleted (muscle glycogen may fall to zero during exhaustion), the posttraining and postcompetition diets should be given primary consideration. Based on these findings, the runner should be given a carbohydrate-rich diet following the final hard training session prior to competition.

The precompetition meal and fluid ingestion have been questioned by several investigators. Mathews (32) suggests that a high protein diet prior to strenuous endurance-type exercise is detrimental because protein metabolites are eliminated only through the urine. During stress situations, such as long-distance running, the kidney reduces its functioning and, therefore, allows for considerable acid accumulation. Mathews states that the more rapid the accumulation of acid, the sooner fatigue will be observed. Therefore, meats, eggs, fish, and high cellulose foods such as lettuce and seed-containing vegetables should not be eaten for 48 hours prior to a distance race. Fats are slow in leaving the upper gastric tract and should not be included in the preevent meal.

On the other hand, several items of research have shown no detrimental effects of a light meal on running endurance (2, 3, 9, 42). Asprey (2, 3) concluded that eating a cereal-and-milk meal (about 500 calories) one-half hour, one hour, or two hours before running either the mile or 2-mile had no adverse effect on the runner's time.

Little, Strayhorn, and Miller (27) attempted to determine the effect of water ingestion on the capacity for exercise by studying the physiological responses to standard exercise on a treadmill and to performance running. The subjects were required to ingest one liter of water in early experiments and 1.5 liters in later experiments immediately prior to exercise. After analysis of the data, the authors reported no significant changes on the variables tested following water ingestion.

Relative to preevent food and fluid ingestion, it would appear that no detrimental effects should be anticipated. However, one might realize that a heavy meal or the ingestion of any matter that might maintain the stomach in a distended condition might seriously interfere with the contraction of the diaphragm and, therefore, impair respiration, a vital element in the runner's ability to perform high level endurance work.

Summary

Definite contradictions seem to prevail among various facets of training for long races. The speed work normally associated with interval training has not been found to produce the phenomenal results anticipated when compared to long, continuous runs. Current findings seem to suggest a need for a combination of both speed (interval) and overdistance training. For minimal improvement in cardiorespiratory endurance, a runner must run at a speed that will elicit a heart rate of 130 beats per minute, or about 50 percent of his maximal oxygen uptake capacity. To improve endurance at a maximal rate, a man must run at a speed that will require a maximal heart rate and/or a near maximal oxygen uptake. Minimal running improvements have been observed with two training sessions per week and maximal improvements with five and six workouts per week.

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3. IN THE LONG RUN

Physical preparation for long-distance races is of primary consideration to the runner. Yet there are many factors aside from a sound training program that must be evaluated and planned by the distance coach and runner if a successful performance is to be achieved. Such factors as the race pace, environmental conditions, dehydration, and warm-up can play important roles in the optimal utilization of the runner's energy reserves and potential capacity. This chapter will present research for the understanding and evaluation of the performance in the long run.

Physiological Responses During the Distance Race

Energy Requirements. The magnitude of systemic changes (i.e., body temperature, sweat rate, heart rate, etc.) during distance running is dependent upon the runner's rate of energy expenditure. As has been pointed out earlier, the rate at which a man can run for any extended period of time is dependent upon his aerobic capacity (maximum oxygen consumption capacity). Generally speaking, a runner with a greater capacity for oxygen consumption (ml/kg/min) can perform submaximal work at a higher level than another runner with a lower consumption capacity, and yet both men might be utilizing equal fractions of their maximum oxygen consumption capacity. Also one must consider that the longer the race, the smaller will be the fraction of the maximal oxygen consumption that the runner will be able to utilize. As an example, a runner might be able to utilize 100 percent of his maximum oxygen consumption while running the two-mile, while during a 10-mile race he might be able to sustain only 80 percent of this same aerobic capacity.

In an attempt to substantiate this concept of energy expenditure during strenuous work, several pieces of interesting research might be cited. Margaria (23) observed that the mechanical efficiency of running is only about five to seven percent higher in the athlete than in untrained subjects. He concluded that a trained runner can perform better than a nonathlete, not so much because of his greater skill as because of his greater capacity for oxygen consumption. Comparison of the energy utilization during various competitive distances has shown that in the one-mile, oxygen consumption during the race may approximate the maximum oxygen intake, and the oxygen debt may comprise 50 percent or more of the total oxygen demands (10, 23).

Kollias (21) has suggested that in cross-country running, for 5 miles, a relatively steady state is reached, and the average oxygen consumption is usually less than the maximal aerobic capacity of the runner. Cross-country runners were reported to utilize 82-85 percent of their maximum oxygen consumption during a simulated five-mile treadmill run (21). It was concluded that cross-country running, which requires about 80 percent of maximum oxygen consumption, can be sustained for a relatively long period of time, and for brief intervals can be increased to over 90 percent of maximum. It was theorized that runners in the future may be able to average 90 percent utilization of their maximum.

More recent research (10) has shown that well trained distance runners can utilize in excess of 90 percent of their maximal oxygen capacity for the last 15-20 minutes of a simulated 10,000-meter run on a treadmill. Results of this study are illustrated in Figures 3 through 7. Figures 3 and 4 present the oxygen cost and fractional utilization of the maximal capacity for three distance runners. During these treadmill performances, the runners were permitted to vary the speed of the treadmill, therefore selecting their own running paces. The pace changes were individually typical and would demonstrate that during competition, it is unlikely that true steady-state running does exist (Figure 5).

Hedman (13) and Astrand (3, 4) have noted similar aerobic capacities among other groups of endurance athletes. It was found that cross-country skiers can ski for two hours or more with an oxygen intake of about 80 percent of maximum. Additional research is needed to identify how much of the running improvement in early training is associated with an increased maximal oxygen uptake or with a greater fractional utilization of this capacity.

Respiration. Associated with the high rate of oxygen consumption during long-distance running is the capacity to breathe extremely large volumes of air for extended periods of time (10, 21). As a point of reference, the average man breathes approximately 6 liters of air per minute at rest. Kollias (21) observed volumes (BTPS) in excess of 150 liters per minute during a simulated 5-mile cross-country run. Figure 6 illustrates the pulmonary ventilation for three men during a treadmill-simulated 10,000-meter run. These men were able to ventilate between 120 and 145 liters of air per minute for more than 20 minutes of running. Other well trained athletes have been found capable of such large pulmonary volumes only during the final stages of an exhaustive run.

Heart Rates. Although the coach and runner are seldom technically equipped to make determinations of physiological stress during distance running, it is feasible to record immediate postexercise (first 10-20 seconds of recovery) pulse rates. Such recordings, taken for 10 seconds and multiplied by six, will provide a fairly accurate measure of the heart (beats/minute) during the distance run. Additional recordings taken for 15 seconds at the end of each minute of the first 5 minutes of recovery can be utilized to evaluate the performance. By relating such information to the runner's time, pace pattern, and other race conditions, the coach and runner will be better prepared for future competition.

Heart rate responses during distance running (2-26 miles) have shown an inverse relationship during the early part of the race when related to the racing distance; that is, the longer the race, the lower the runner's heart rate during the initial phase of the race. This response is an obvious function of the runner's pace. However, regardless of the competitive distance, the runner's heart rate has been found to reach a maximal level during the latter stages of the race (10). Figure 7 illustrates the heart rate responses of three men performing a simulated 10,000-meter run. It must be remembered that each of the runners employed different pace patterns during the run (SK ran slow-fast-slow, SL ran fast-slow-fast, and EW ran slow-fast-faster); however, all of the men recorded their maximal heart rates.

Fatigue. While most coaches and athletes associate an exhaustive performance with a large oxygen debt, slow heart rate recovery, and extremely high lactic acid levels, the distance runner may not experience these physiological responses in the proportions one might expect. During the initial seconds of a race, the runner's circulatory and respiratory systems are somewhat delayed in their adjustment to the sudden burst of energy expenditure (see Figures 3, 6, 7). Since the immediate oxygen requirements are greater than the supply, the runner builds an oxygen deficit and an accumulation of lactic acid. However, studies by Bang (5), and more recently by Kayne and Alpert (20), have failed to reveal a close relationship between arterial lactate concentration and oxygen debt.

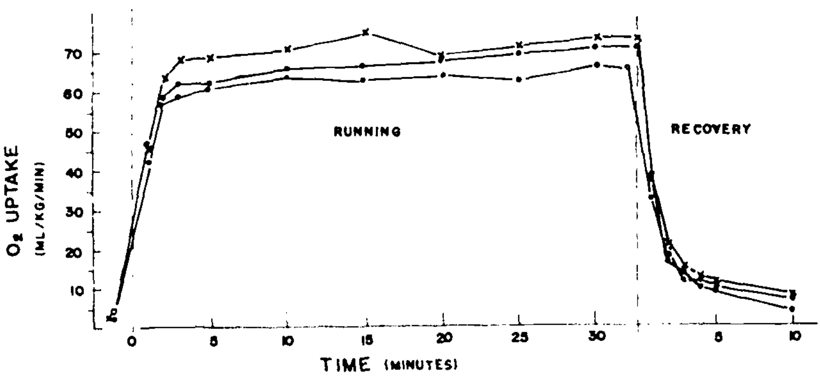

FIGURE 3. Oxygen consumption (ml/kg/min) for three distance runners performing a maximal 10,000-meter run.

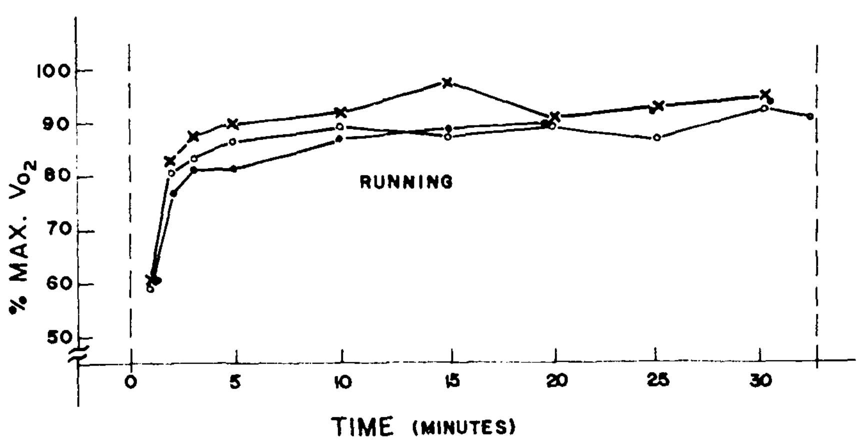

FIGURE 4. The percentage of maximal oxygen uptake utilized by each runner illustrated in Figure 3.

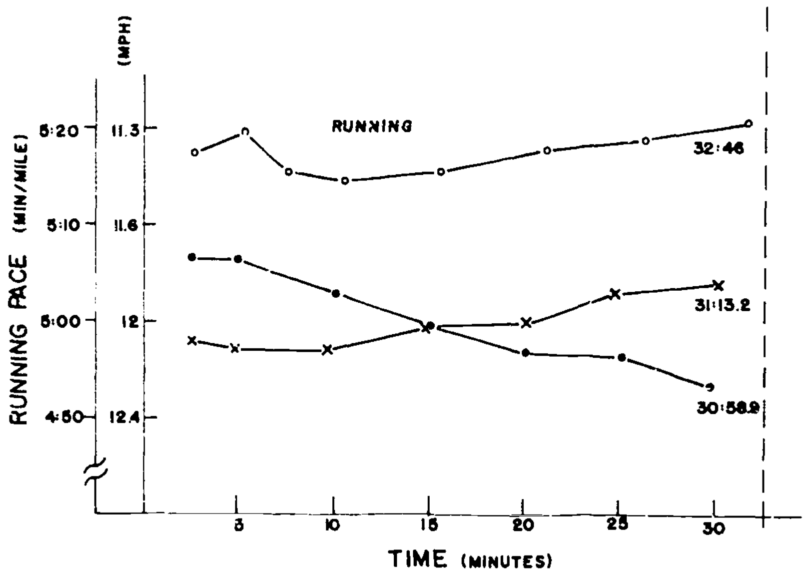

FIGURE 5. Variations in running speed for the three runners mentioned in Figures 3 and 4 during a simulated 10,000-meter run.

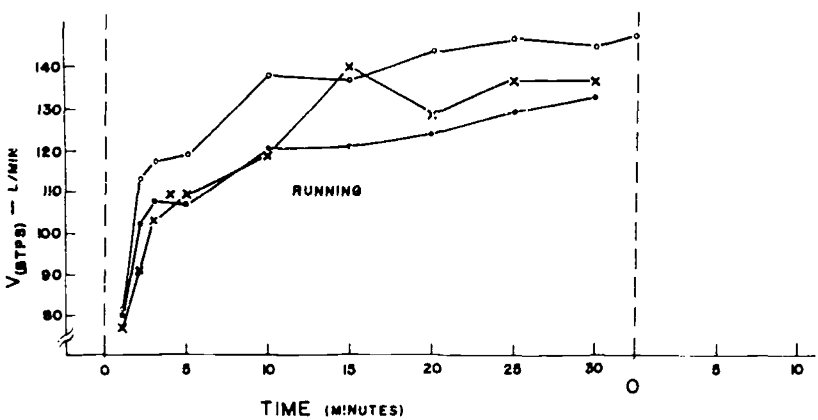

FIGURE 6. Pulmonary ventilation for three distance runners during a simulated 10,000-meter run.

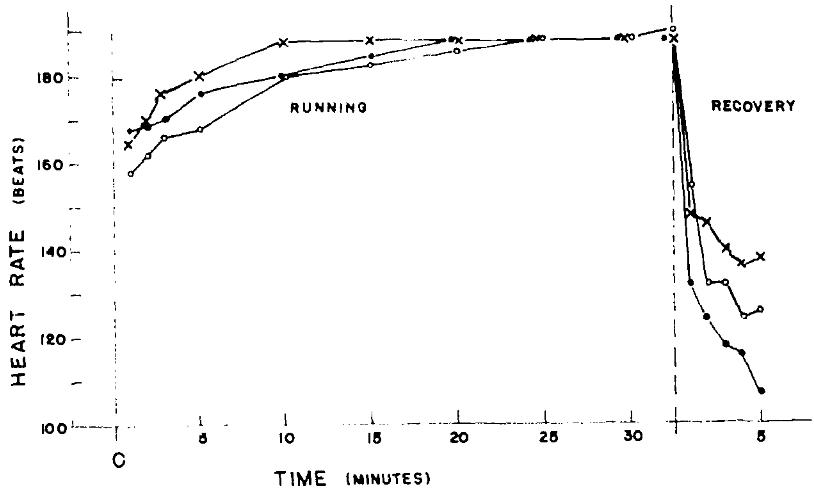

FIGURE 7. Heart rate responses during a simulated 10,000-meter run.

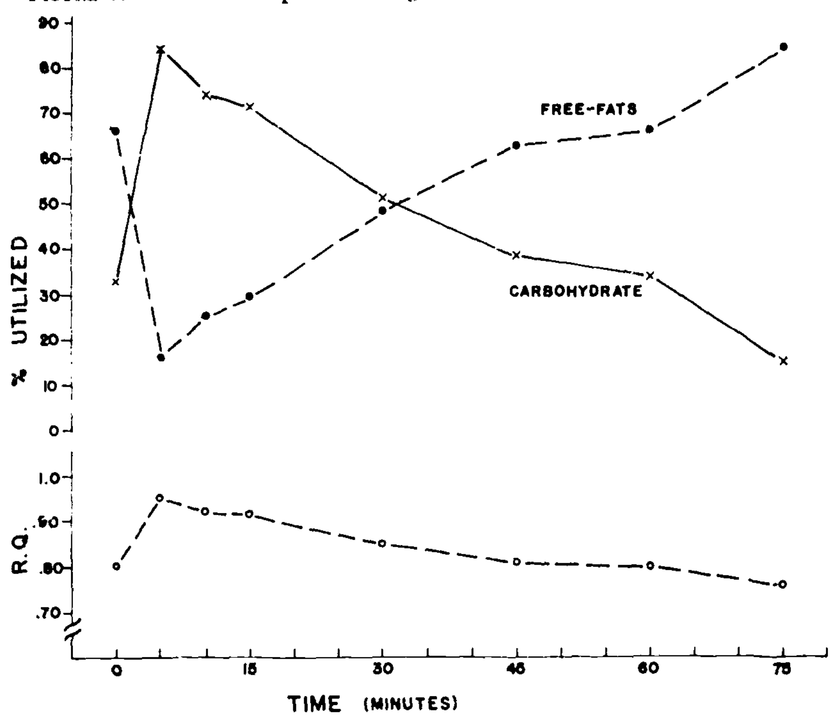

FIGURE 8. The percentage of energy obtained from free fat and carbohydrate utilization during 75 minutes of exhaustive treadmill running, as determined by the respiratory quotient.

Most authorities agree that the accumulation of lactic acid in the blood gives a good objective measure of the runner's degree of exhaustion. Astrand (4) has shown that the blood lactate may reach a high of 140 mg/100 ml blood when a final sprint is preceded by 35 minutes of hard work. As a point of reference, 10 mg of lactic acid per 100 ml of blood is considered a normal resting value. Costill has observed values of 38-47 mg/100 ml blood in men following 31-32 minutes of exhaustive running when the final sprint is not permitted (10).

It has been known for many years that when the concentration of lactic acid in blood is increased by exercise, a large fraction of it is removed by the liver, kidneys, heart, and skeletal muscles, even during the course of the activity (8, 12, 15, 22). The relationship between the blood lactate level during exercise and the magnitude of the runner's oxygen debt is increased as the duration of the exercise is increased. Rowell (28) has shown that the lactic acid produced during exercise reached a peak concentration during the first 10 minutes of running. However, half of the concentration had been removed by the end of 27.5 minutes of running. It was concluded that during prolonged exercise, a very significant portion of the lactate produced (perhaps 50 percent) is removed by the liver. These findings support the concept offered by Astrand (4) that the longer the race the lower the blood lactate concentration. While no physiological mechanisms have been identified, several researchers conclude that a different type of fatigue must exist during long-distance running as compared to exhaustive work of short duration.

An explanation of the fuels utilized during the performance of a long run can shed additional light on the site of fatigue. Determination of the respiratory exchange ratio between carbon dioxide produced and oxygen consumed revealed that carbohydrates are utilized more readily with a rise in work intensity (9). However, during prolonged, heavy exercise there appears to be a shift from the utilization of carbohydrates to the metabolism of fatty acids. Figure 8 illustrates the average fractional utilization of carbohydrates and fats during 75 minutes of exhaustive running as indirectly determined by the respiratory exchange ratio.

More direct methods have been used by Ahlborg and others (2) to assess the influence of heavy, prolonged physical exercise on the content of glycogen in the working muscles. The subjects of these investigations were required to exercise continuously on a bicycle ergometer until they had to stop because of exhaustion. Needle biopsy methods were employed to determine the quantity of muscle glycogen before and immediately after the exercise. A close correlation was found between performance time and the initial muscle glycogen content. There was also a fair relationship between muscle glycogen decrease and performance time. These relationships indicated that the local glycogen stored in the working muscles is a determining factor for the ability to perform long-term exercise (i.e., the higher the muscle glycogen content, the faster the distance runner's performance time). The only other parameter measured by Ahlborg that showed changes of such magnitude as to have a limiting effect on further performance was the blood sugar, which was found to be extremely low at the end of exercise.

Fatigue during distance running is, therefore, a function of the glycogen stored in the muscle. As the available carbohydrates are consumed, exhaustion becomes imminent. However, additional research is needed to identify the role and apparent inability of the free fatty acid metabolism to compensate for lack of muscle glycogen.

Fluid Replacement. Extensive research by Saltin and others (11, 29, 30) has demonstrated that water and salt loss in sweat and the depletion of sugar stored in the muscle (glycogen) are the major factors which cause fatigue and impair performance during severe exercise of long duration. If it were possible to replace sweat losses and to maintain a sufficient supply of glucose during a distance race, the runner's performance would most likely be improved.

Early research has shown that moderate to heavy exercise inhibits the ability of the stomach and small intestine to empty (7, 14). However, more recent findings have shown that intestinal absorption is not significantly affected by exercise and that gastric emptying is only slightly decreased. It is known that gastric emptying is dependent in a major way on the type of solution ingested and on its concentration. While water is easily absorbed from the stomach, an isotonic saline (water plus 0.85% sodium chloride) solution empties it even more rapidly ([illegible]1). However, the addition of even small amounts of glucose (5%) to water causes a marked inhibition of gastric emptying (16, 17). These findings would indicate that the water and sodium chloride lost during a distance race can be replaced by ingesting sufficient volumes of saline-like solutions. On the other hand, the glucose utilized during a race can only partially be replenished since approximately 100-200 gm of glucose are utilized per hour while only 50 gm of glucose can be absorbed from the stomach during the same period (29, 30). Attempts to ingest larger amounts of glucose will inhibit the fluid absorption by the stomach and retain large amounts of fluid in the stomach, which can produce abdominal discomfort during the race.

On the basis of the preceding discussion, the runner competing in extremely long races of 15-50 miles, or in hot, humid climates, should force himself to consume frequently a saline solution with limited amounts ot glucose added. Because of the difficulty experienced by the runners while ingesting fluids and the discomfort caused by large amounts of fluid in the stomach, small frequent feedings appear to be most efficient and effective. The confusion caused by competition and the absence of thirst can be very misleading to the runner. It is not unusual for an extremely dehydrated runner to experience very little or no desire for water. The athlete must be aware of his body's demands for sedium chloride, water, and glucose and must realize that the thirst mechanism is an inadequate indicator of bodily needs.

Warming Up for the Distance Race

The continual controversy concerning the advantages and disadvantages of warming up has been discussed from many angles but remains unresolved (18). Some coaches advocate the importance of warming up for distance on the basis of the following claims:

1. Warm-up increases the muscle temperature and thereby increases the contractile force of the muscle.
2. Warm-up will help to prevent muscle and tendon injuries.
3. Warm-up supposedly brings on second wind more rapidly.
4. Warm-up provides an opportunity to rehearse the pace and relaxation which will be performed during the actual race.

While these potential contributions appear theoretically sound, very little research has been conducted that provides convincing evidence for benefits in distance running. Astrand (3) has reported a five-percent increase in the maximal oxygen uptake capacity of men following a warm-up. Since the distance runner's performance is reliant upon the capacity of his respiratory and circulatory systems to deliver oxygen to the active muscle tissue, this factor would be of importance during runs which utilize 100 percent of the maximal oxygen uptake. However, races which are performed below this level might not be affected by a lack of warming up. As an example, a miler or two-miler might benefit from warm-up while the marathoner might not.

While studying pre- and post-competition rectal temperatures, Robinson (27) noted a decided detrimental effect of warming-up in the heat. Performing a 10,000-meter run in 90°F heat caused the runners to elevate their rectal temperatures approximately 5°F. However, as a result of warming-up, one runner's pre- and post-race rectal temperatures were 1.5°F higher than those of a second runner who did not warm-up. It appears quite sensible for the runner to eliminate any warm-up prior to a distance race in the heat where one of the major performance limitations is overheating.

While some coaches and researchers feel that warming up is greatly overemphasized, it is apparent that most athletes prefer to continue with traditional techniques. Because of the physiological and psychological complexity of distance running performance, this approach appears to be a wise one.

Pacing the Race

Pace is an important but controversial concept. Karpovich (19) suggests that the maximum speed which can be developed depends on the extent to which the metabolism can be raised and on the efficiency of muscular performance during exercise. But the oxygen requirements of running increase very rapidly as the velocity of work of the runner becomes greater. Several physiologists have, therefore, advocated an even or steady pace over long distances.

Robinson (26) studied the effects of variable pace on the oxygen requirements and blood lactates of four well conditioned subjects during exhausting treadmill runs. In one experiment, a subject became exhausted in 3.37 minutes while running at a constant speed of 13.9 miles per hour. However, the same runner was able to cover the same distance (1362 yards) in the same total time with a lower oxygen requirement and less blood lactate when he ran the first 2.37 minutes at 13.5 miles per hour and the last minute at 14.9 miles per hour. On the other hand, when the first 2.37 minutes and last minute were run at 14.9 and 13.5 miles per hour, respectively, the subject experienced higher oxygen requirements and higher blood lactate than while running at the constant speed of 13.9 miles per hour. It must be remembered that such results may be specific to races of relatively short duration.

In a study of heart rate responses to various pace patterns (slow-fast, fast-slow, and steady) during the running of the mile, it was noted that the slow-fast pace pattern required less overall energy than the other pace patterns (6). However, the fast-slow pace pattern was identified as pattern which produced the fastest one-mile times.

Adams (1) conducted a somewhat more controlled investigation on the energy required to run a 4:37 mile, which was simulated on a treadmill. A steady pace run (Plan 1) consisted of a constant 69.25 seconds per 440-yards pace throughout, while a fast-slow-fast run (Plan 2) involved consecutive 440-yard times of 64, 73, 73, and 67 seconds, and a slow-fast run (Plan 3) required 440-yard times of 71, 71, 67.5, and 67.5 seconds. It was concluded that when the running pace varied from a steady pace, a significantly higher oxygen debt was incurred and that the steady-pace plan was the most efficient means of utilizing one's energy reserves and, hence, physiologically best for accomplishing the fastest time in middle and distance running.

Additional support for steady pace work was offered by Mathews (24). The mechanical efficiency of exercise was computed while the subjects were riding a bicycle ergometer at 60 revolutions per minute for six minutes with the following distributions of resistance—steady, light-heavy, and heavy-light. His findings indicated that steady pace was significantly more efficient with regard to oxygen consumption.

By means of radio telemetry, heart rate responses were used by Sorani (31) to evaluate steady pace, slow-fast pace, and fast-slow pace during a run of 1320 yards. On the basis of net cardiac cost, no evidence was found that would indicate a detrimental effect caused by varying the pace during a 1320-yard run.

In the light of these research findings, one must conclude that total agreement does not exist relative to the most optimal pace one should employ during a distance race. However, the steady pace plan appears to have gained the greatest scientific support.

In selecting the best running speed for any given distance race, the coach should remember that the runner is limited by his capacities to consume oxygen and to tolerate fatigue. A series of investigations concerned with the energy expenditure of runners during various distance races has demonstrated a high relationship between the fractional utilization of one's maximal oxygen uptake (Max. V_{O_2}) capacity and the length of the race (10). Runners competing in the 2-mile were found to consume 100 percent of their Max. VO_2, while 6-milers and marathoners utilized 88-94 percent and 68-75 percent, respectively. Additional research is needed to assess the running speed of champion distance runners as related to their fractional utilization of the Max. V_{O_2}. Such information would assist in predicting the potential capacity of any given runner to perform at a given distance.

Summary

During the early stages of a race, the body utilizes carbohydrates and very little fat. However, during the final phase of the race, the greatest source of energy is provided by the available fats as the carbohydrate stores become depleted. Fatigue seems to be associated with the exhauston of stored energy rather than an acculumation of metabolic waste materials.

Each runner is limited in his capacity to deliver oxygen to the working muscles (maximal oxygen uptake). The rate at which each man

can run a given distance is dependent upon this capacity. In the two-mile run, the oxygen requirement may be 100 percent of the runner's capacity, while during a 10-mile race, he might be able to sustain only 80 percent of his capacity.

The lactic acid formed during the early stages of a race has been found to be removed from the blood by the liver, kidneys, heart, and skeletal muscles during the course of the run. The best technique to use for removing lactic acid between bouts of hard running is to jog easily throughout the recovery period.

The runner competing in extremely long races of 15 to 50 miles and/or in hot, humid climates should force himself to consume an isotonic saline solution with limited amounts of glucose added.

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4. ENVIRONMENTAL INFLUENCE ON DISTANCE RUNNING

Man's capacity to perform exhaustive running for prolonged periods has been shown to impose tremendous stress on various systems of the body associated with increased muscular metabolism. In addition to the metabolic overload, several environmental factors can complicate the physiological ability of the competitor to achieve a maximal performance. The two most common environmental conditions that deter distance running performance are temperature extremes and the hypobaric conditions of high altitude.

Running in the Heat

The body's kinetic activities result in an internal heat surplus (metabolic heat) that must be partially eliminated if the runner expects to survive such thermal stress. During distance running, a very large portion of the excess internal heat is lost through sweat evaporation. Thus far, we have considered the principal tasks of the circulatory system as being the delivery of nutrients to the active tissues and the removal of metabolic waste. However, one of the most important functions of circulation during prolonged exercise is the regulation of heat transfer from the metabolically active muscles to the body surface. Because of this added demand on blood flow, body temperature regulation and circulatory capacity are significantly influenced by the environmental temperature and humidity.

Estimates have been made showing variation of overall blood flow to the skin from 0.16 liters/m^2/min in a nude resting man exposed to a temperature of 28°C to 2.6 liters/m^2/min in men working in an extremely hot environment (8, 11). Robinson (19) has reported that a man who is well acclimatized to work in hot environments can maintain thermal equilibrium with a total blood flow to the skin in 112°F heat (18% humidity). In this situation, approximately 20 percent of the subject's cardiac output was being circulated through the skin.

Under competitive running conditions, the circulatory system is frequently stressed maximally in meeting the demands of the active muscle. When attempts are made to perform maximally in warm humid conditions, circulation cannot perform both tasks (body temperature regulation and nutrient delivery to the muscles) to the complete satisfaction of the body. The runner's performance is impaired and overheating becomes a serious problem.

Marathoners running at 70 percent of their maximal oxygen uptake capacity in three thermal climates have demonstrated a significant increase in heart rates, rectal temperatures, and sweat loss in 87°F (34% RH) as compared to 73°F (38% RH) or 60°F (32% RH) (6). Figure 9 illustrates the mean rectal temperature responses of these subjects during a 10,000-meter run at marathon racing pace. Rectal temperatures increased 3.15°F in the 87°F condition and 1.9°F in the 60°F climate. The men lost an average of 2.9 pounds during the run in the hottest environment and 1.3 pounds in the coolest condition. These results, therefore, demonstrate the three critical problems which confront the distance runner in the heat: rapid dehydration, overheating, and reduced circulatory potential.

Robinson (20) has measured rectal temperatures of .106°F at the finish of a race, while Joy (14) has recorded 104°F rectal temperatures in runners at the completion of the Boston Marathon. Overheating may pose three major threats to the runner: heat cramps, heat exhaustion, and heat stroke.

Prevention of heat cramps lies in taking adequate salt in the diet. Taylor (28) has shown that under extreme conditions, 13 to 17 grams of salt per day will maintain electrolyte balance. Greater salt intake than this is normally excreted by the kidney and may cause nausea in many individuals (7). If the volume of water replacement is extremely large during a marathon race, some small replacement of salts may be prescribed. However, Pugh (18) has observed quite normal blood sodium and chloride following a marathon race in a 74°F (52-58% RH) thermal climate. Further research under conditions of greater thermal

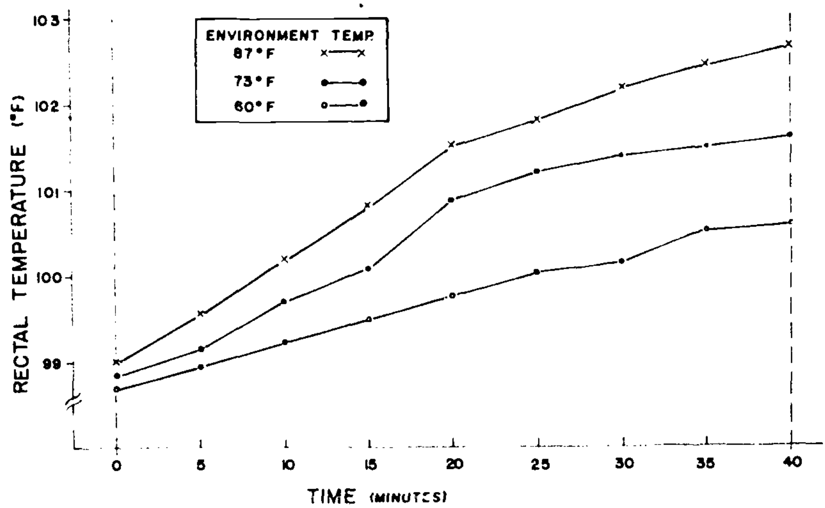

FIGURE 9. Rectal temperature responses of a distance runner performing at 70 percent of his maximal oxygen uptake in three thermal climates.

stress would seem of value in defining the need for water-salt replacement during a distance race.

It has been suggested by deVries (7) that heat exhaustion occurs when the limitations of the cardiovascular system are exceeded. The acute dehydration that accompanies profuse sweating while running in the heat causes a reduction in extracellular fluid volume and a significant lowering of the runner's total blood volume (18). Heart rate responses during dehydration of 4.5 percent of one's body weight indicate a significantly greater circulatory demand for a given running speed (16). Mean weight losses at the end of a marathon race have been found to exceed 5 percent of the runner's prerace body weight (18). Buskirk (4) has reported varied weight losses, from 2.5 to 7.4 percent, in the marathon runner, but he was unable to identify a performance decrement among the runners. Running speed (pace) was fairly constant by each runner with no letdown in pace near the end of the race. This evidence implies that tolerance to dehydration is an essential condition of successful distance running under warm conditions (18).

Heat stroke poses a serious problem for men who are stimulated to extend their energies and who continue running under any combination of the following conditions: high ambient temperature, high relative humidity, excessive sweat loss, and extremely high internal body temperature (106°F or higher). This is especially true when the runner is unacclimatized to heat. Pugh *et al.* (18) observed evidence indicating that tolerance of a high body temperature is a necessary condition of success in marathon runners.

The runner should be aware of the thermal balance that must exist between internal heat production (metabolism) and additional heat gains from a hot-humid environment. Radiant heat gains from the sun can also compound the problem of heat gain from the environment. Such factors play a vital role in determining the most optimal pace that the runner can sustain in the longer races.

Although the runner's skin is not generally covered in a manner that would impair heat loss, some thought should be given to the racing costume. Lee (15) suggests that the following principles can be applied to promote evaporation: (1) loose-fitting clothing should be worn to expose the wetter skin; (2) jerseys should be perforated to increase ventilation; (3) clothing should be light in color to reduce radiation gains; and (4) the skin should be wetted if it is dry to promote evaporation.

Wetting the clothing is a special problem because it extends the evaporative surface to the outer margin of the clothing and create a humid microclimate for the runner (3). One practice frequently employed by some runners and spectators during long runs in the heat is to spray the runner with water. This approach to cooling may cause more problems than it solves.

Acclimatization to heat. When men who are not accustomed (unacclimatized) to the heat attempt moderate running on a hot day, they may become overheated within one or two hours. Robinson (21) notes that such runners show significantly higher rectal and skin temperatures and reduced differences between the internal and skin temperature. Metabolism and heart rates increase in proportion to body temperature, and the runners may show signs of circulatory instability. With repeated daily exposure to the same combination of work and heat stress, highly trained runners can expect complete acclimatization within four to eight days (21).

After acclimatization, the runner will experience a dramatic improvement in his ability to perferm. Subjective discomfort practically disappears, body temperatures and heart rates are lower, and sweat is more profuse and dilute (less salt is lost). Acclimatization can be induced by short, intermittent work periods in the heat, e.g., 2 to 4 hours daily (2). Inactivity in the heat offers very few of the benefits of acclimatization.

Some researchers have suggested that because physical exertion causes excessive thermal stimulation to the runner, some degree of heat acclimatization can be attained through training. This would mean that a man who is required to train in a cool climate would still gain a partial adjustment to similar work in the heat. Strydom (27) has demonstrated that conditioning programs administered in relatively cool conditions had only a limited effect on a man's state of acclimatization to 5 hours of moderate work in the heat. When exposed to 10 days of heat and exercise for 5 hours each day, rectal temperatures and pulse rates decreased within the first four to five days, but sweat rates reached a maximum value only on the tenth day. It was concluded that although training may improve performance under conditions of heat, it certainly cannot replace acclimatization by actual exposure. Runners who must train under relatively temperate conditions must be alerted to the possible consequences of an "all-out" effort in a hot-humid thermal climate. The runner should take the necessary steps to preacclimatize to the warmer conditions. Robinson (21) has concluded that a strenuous interval training program (e.g., repeated fast runs alternating with one- to four-minute periods of rest or slow activity) in a cool environment is more effective in preconditioning physically fit young men for work in the heat than continuous moderate running.

Running in the Cold

It is generally believed that the heat produced by exercise provides the necessary warmth to maintain a thermal equilibrium while running in the cold. The author has observed one subject's rectal temperature to be lower at the end of a 25-mile run in 25°F air temperature than was recorded before the exercise (6). Although the subject was warmly clothed (two sweat suits), his rectal temperature decreased from 99.2°F to 98.7°F.

While further research thus seems warranted, one might theorize that under extremely cold conditions, the quantity of heat lost may exceed that produced by muscular activity. Although it is unlikely that performance would be impaired by cold conditions, extreme weakness and collapse may occur in hypothermia. Because of their minimal body fat composition, the distance runners are generally poorly suited to cold exposure.

Despite low environmental temperature, men have been found to sweat quite profusely, resulting in a substantial weight loss and surprisingly low skin temperatures (6). This accumulation of sweat in the clothing and on the skin provides a rapid mechanism for heat loss by conduction to the cold, wetted microenvironment surrounding the runner.

A significant group of investigators has found no evidence of cold acclimatization in man (13, 24, 25). Some cold adjustment has been observed among men during resting conditions, but evidence is lacking concerning running performance and cold exposure.

Running at High Altitude

Numerous investigations have reported the physiological responses of men to working performance at high altitude. Probably the best single source of past research on this topic has been compiled in *The Effects of Altitude on Physical Performance*, published by The Athletic Institute in 1967.

Distance-running performances as recorded in the past have been established under climatic conditions that were relatively compatible with the physiological make-up of man. However, the atmosphere which houses man on earth is not uniformly optimal for prolonged exhaustive exercise. Acute exposure to the low partial pressure of oxygen at higher elevations has been shown to impose detrimental effects on work capacity.

Increase in altitude imposes added work on the heart and lungs of the nonacclimatized runner (23). Potts (17) is of the opinion that oxygen supply and energy reserves are adequate for an "all-out performance" for periods up to two minutes at altitudes of 7,500 feet or less. At Boulder, Colorado (elevation 5,400 feet), the difference in performance time as compared to a low altitude performance is between 7 and 10 seconds per mile. In the three-mile, Lajos Mecser of Hungary recorded a 13:40.4 at the 5,400-foot elevation as compared to a 13:17.0 performance at a lower altitude, which would support the suggested differential in running performance.

General agreement exists among researchers that maximum aerobic capacity (Max. V_{O_2}) is reduced during acute exposure to an altitude of 7,500 feet (1, 5). However, the degree of reduction has been shown to vary from a very small amount to as much as 28 percent (26). The average decrement of about 8-10 percent fits the regression line for maximum oxygen consumption and lower atmospheric pressure (5, 9). During moderate work at 7,500 feet elevation, one's pulmonary ventilation increases significantly (12). Faulkner (9) suggests that training at moderate altitude results in a greatly increased capacity for pulmonary ventilation, unattainable during sea-level training.

While the decrements observed in both working capacity and maximum oxygen consumption are sizable during acute exposure, it has been concluded that these values are even lower after a few days of acclimatization. For this reason, some researchers have suggested that the runners should not go to altitude until the day of competition unless an adequate period is allotted for acclimatization. Robinson (22) recommended that a runner pace the first part of a race slower or at least at the same speed as the latter part to delay the onset of fatigue.

During acclimatization to moderate altitudes, the hemoglobin concentration and the number of red blood cells are noticeably increased; this results in greater oxygen-carrying capacity. Hemoglobin values have been found to increase by 10 percent, while hematocrits increased an average of 4 percent (9). However, a decrease of 20 percent in plasma volume was believed to account for the total increase in hematocrit. These findings would indicate, therefore, a substantial increase in the corpuscular hemoglobin concentration and the advantage of increasing the oxygen carrying capacity of the blood with only a slight increase in blood viscosity. Acclimatization of men to altitude seems to lessen the differential in physiological and performance capacities at high altitude as compared to sea level.

After acclimatization at an altitude of 10,170 feet, runners have not shown improved performances at sea level by their exposure to the hypoxic conditions at altitude (11). On the basis of these findings, one would not anticipate an advantage in favor of the athlete who is native to moderate altitude when competing at lower elevations.

Summary

Individual variations in response to the environment make it difficult to predict the effects of heat, cold, and high altitude on distance running performance. Running in the heat places great demands on the circulatory system and results in a slowing of performance. The three critical problems which confront the runner during distance runs in the heat are acute dehydration, overheating, and a reduction in the circulatory potential. Runners who must compete in the heat should make a special effort to train under similar conditions.

Distance running performances at altitudes above 5,000 feet are substantially impaired. Regardless of the duration of acclimatization, it is unlikely that any runner will perform as well at higher altitude as he might at sea level. At an elevation of 5,400 feet, a man can expect to run 7 to 10 seconds slower per mile.

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